Lightweight Thrust Chamber Composite Overwrap Lessons Learned

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ABSTRACT

The manufacturing, design, and analysis of filament wound carbon fiber/polymer composite overwraps for additively manufactured, copper combustion chambers are a critical part of NASA's Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project. Ideally, the composite overwrap acts as a light-weight structural jacket and allows significant weight reduction of the high pressure thrust chamber assembly, reduction of overall cost, and reduced fabrication schedules. Chamber assemblies for 2000 lb. (2k) and 7000 lb. (7k) of thrust have been successfully tested at NASA's Marshall Space Flight Center. Multiple lessons were learned throughout the overwrap process development and manufacturing trials. The lessons learned on small scale hardware, such as the 2k and 7k chambers, will guide further composite manufacturing technologies and enable a progression to larger scale assemblies with greater structural loads. Material performance requirements, manufacturing process development, and surface preparation were evaluated during the small chamber trials, with the broad thermal requirements of the resin being the primary driver for material selection and processing. Both epoxy and bismaleimide (BMI) materials were evaluated with respect to both performance in the hot-fire test and ease of fabrication. Separately, surface preparation procedures were studied with the goal of providing a smooth chamber surface to promote a non-bonded overwrap. Recent testing of the 7k trust chamber has provided data in Non-Destructive Evaluation (NDE) and processing in order to continue to evaluate the performance requirements stated.

1 INTRODUCTION

The broad goal of the NASA's Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project is maturation of novel design and manufacturing technologies to increase scale, significantly reduce cost, and improve performance for regeneratively-cooled thrust chamber assemblies; specifically the combustion chamber and nozzle for government and industry programs [1]. An overview of the technology developments within RAMPT are presented in Figure 1. RAMPT builds upon technologies developed under NASA's Game Changing Development Program's Low Cost Upper Stage Propulsion (LCUSP) project as well as on other technology development projects [2-3]. Manufacturing technologies developed under LCUSP included Laser Powder Bed Fusion (L-PBF) of Copper Alloy GRCop-84 and Electron Beam Free Form Fabrication (EBF3) with Nickel Alloy Inconel 625 to produce a rocket combustion chamber within a shorter schedule and at a lower cost [4].

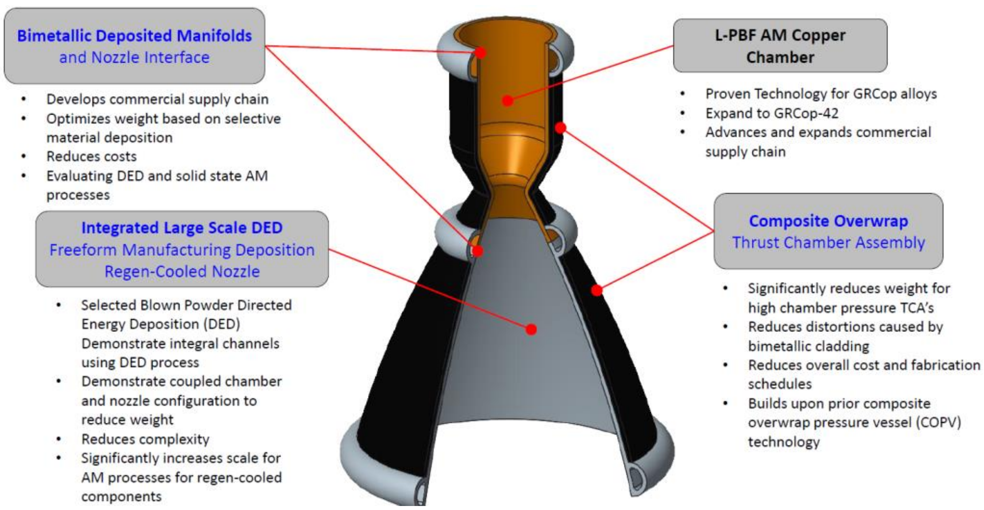


Figure 1. Overview of Manufacturing Technologies within the RAMPT Project

RAMPT will continue to focus on additive manufacturing processes for the thrust chambers, as demonstrated in LCUSP, to enable high strength-to-weight metals for manifolding that can be machined easily for inlets and instrumentation. The liner is produced by L-PBF of Copper alloy GRCop-42. Copper alloys are desirable for chamber liners for their high thermal conductivity, which allows for effective wall cooling to keep the chamber hot wall in a high strength temperature region. The RAMPT project has included composite overwrap development for structural support of the chamber liner. Composites offer much higher strength-to-weight ratio than the traditional metals utilized for structural support in chambers. It is anticipated that the LCUSP developed ability to produce closed wall copper alloy liners along with the advances in composite overwrap fabrication will allow the chamber to meet weight, schedule, and cost saving goals.

Composite manufacturing throughout the RAMPT project has proceeded under a public-private partnership with Auburn University and Kord Technologies with the goal of maturing design and manufacturing technology within the industry. The critical functions of the composite overwrap include, enabling significant weight reduction of the chamber assembly, and reducing overall cost and manufacturing schedules, and reducing distortions in the chamber caused by bimetallic cladding. Throughout this program, many lessons have been learned with respect to the composite overwrap as a structural jacket for the chamber such as material performance over broad thermal requirements, manufacturing process development, and surface preparation. The processing techniques and lessons learned have been applied to filament winding over larger structures of hardware.

The purpose of this paper is to detail manufacturing processes and lessons learned throughout the fabrication and hot-fire testing of composite overwraps for high temperature-high pressure metallic thrust chambers. Material performance requirements, manufacturing process development, and surface preparation were evaluated during the small chamber trials, with the broad thermal requirements of the resin being the primary driver for material selection and processing. Both epoxy and bismaleimide (BMI) materials were evaluated with respect to both performance in the hot-fire test and ease of fabrication.

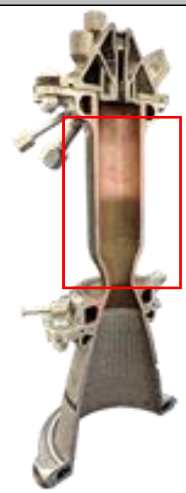
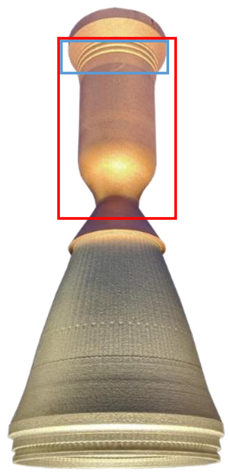
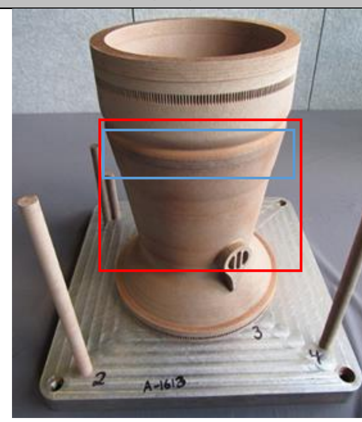
1.1 Application

Rocket engine combustion chambers provide volume for propellants to mix, vaporize and combust, and they serve as structural components to contain the pressure of combustion that is converted to high velocity flow, creating thrust as the gas is expanded through a nozzle. NASA and industry partners have realized the benefits the high strength-to-weight composite overwrap technology offers in tanks and pressure vessels and would like to extend this development to combustion chambers and nozzles. Replacing comparatively lower strength-to-weight metals currently utilized for structural jacket in combustion chambers with the composite overwrap offers the potential to decrease weight up to 50%. Two recent technology advancements allow composite overwrap structural jackets to trade more favorably than in the past. First, advancements in laser powder fusion technologies with copper alloys allow combustion chamber liners to be printed with closed-out channels presenting a solid surface to wrap around. Traditional chambers would have milled channels that had to be closed out, and the closeout material was often a metal that also served as the structural jacket. Chambers and nozzles that utilize propellants to convectively cool the walls that are in contact with the hot gas are known as regeneratively cooled chambers and nozzles. The convective cooling keeps the metal temperature at a value where the metal still has strength when hot gas temperatures in the chamber can exceed 2760 °C (5000 °F). The temperature profiles along the liner to composite interface are similar to the bulk coolant temperature at an axial location and can span from cryogenic [-240 °C (-400 °F) in the case of liquid hydrogen] to temperatures of 232 °C (450 °F) and greater depending on the fuel type and engine cycle. The composite must maintain functionality at these liner to composite temperatures. There are several challenges with this technology that require considerable process development and characterization. These include optimization of the bond between the metallic and composite material, the directional strength of the composite overwrap material, the complex geometry for composite fabrication and the material performance under the intended use environments. Composites for chambers also offer benefits in addition to weight reductions when compared to other additive chamber jacketing techniques since the processing temperature is much lower than that of melted additive metals, greatly reducing the residual stresses and associated warping left in the final part.

1.2 RAMPT Hardware Overview

The various sizes of hardware for the composite overwrap shown in Table 1. The areas of red indicate where the composite overwrap covers the chamber. Ridges have been printed directly into the chamber in order to provide an anchor for the helical and hoop wraps as seen in the blue boxes.

Table 1: Various Thrust Classes of RAMPT Chambers Being Developed

2k-lb_f Decoupled	2k-lb_f Coupled	7k-lb_f Coupled	40k-lb_f Coupled
LOX/RP-1	LOX/LH2	LOX/LCH4	LOX/LH2
			

With the chamber experiencing mainly hoop/burst pressure loads while holding lesser axial loading, the overwrap essentially acts similar to a composite overwrapped pressure vessel (COPV). Therefore, multiple winding patterns have been evaluated based on the individual loading requirements of the chamber. Surface preparation procedures were evaluated to inhibit bonding between the chamber and overwrap.

2 MATERIALS AND CHARATERIZATION DEVELOPMENT

The material thermal requirements varied among the 2k, 7k, and 40k chamber, but it was the high-end of the temperature range experienced by 7k chambers during hot-fire test that drove resin selection. For example, the temperature on the outside of the 7k-lbf in steady operation spans from cryogenic -157 ℃ (-250 °F) at the coolant inlet near the throat to +204 ℃ (+400 °F) at the coolant outlet at the forward end of the chamber. The large temperature gradient and rapid heating/cooling cycles of startup and shut down could lead to high stresses on the composite and ultimately micro-cracking of the resin and/or delamination of the overwrap. To accommodate both the upper and lower temperature extremes, Solvay®'s 5250-4 toughened bismaleimide (BMI) resin was selected for manufacturing development. Manufacturing for the 2k chamber overwrap used EPON® 828/W toughened epoxy as the overwrap experienced temperatures ranging from room temperature to 121 ℃ (250 °F). The 2k decoupled and 7k manufacturing methods are discussed in this paper. Additional, 2k decoupled work, including hot-fire testing was published in Protz et al. [1] and Gradl et al. [5]. The 40k development will be included in future works.

IM7, 12K tow carbon fiber from Hexcel® was selected because of advantageous mechanical properties, familiarity with the fiber from past projects, and its availability at the start of the project.

2.1 Resin Material Characterization

Characterization of Solvay® 5250-4 BMI neat resin blocks as well as composite laminates using Dynamic Mechanical Analysis (DMA) across the temperature experienced by the composite overwrap is underway. Results to be published in future works.

2.2 Surface Preparation of Chamber

The images shown in Table 1, particularly those of the 7k and 40k chambers show significant surface roughness of the additively manufactured thrust chambers and curing the overwrap directly on the chamber leads to a bonded overwrap. This was not ideal due to CTE mismatch between the metallic chamber and the composite overwrap. The metallic chamber shrinks and pulls away from the composite during the initial cool-down of the hot-fire tests which could lead to delamination or tearing damage of a bonded composite. Ultimately the goal is an unbonded overwrap, therefore bonding trials were carried out to evaluate surface polishing and preparation techniques that would discourage bonding during composite cure.

Prior to filament winding, all chamber surfaces are polished with aluminum free 80 grit then 120 grit sandpaper to remove surface roughness and oxidation. The surfaces are washed clean with ethanol then treated with multiple coats of Frekote NC700 mold release agent.

3 MANUFCTURING PROCESS DEVELOPMENT

The composite overwrap was manufactured on with 4-axis filament winders with IM7, 12K tow carbon fiber and either Solvay® 5250-4 BMI (7k chamber) or EPON 828/W epoxy (2k chamber) resin. Two pounds of tension was applied throughout fabrication. The wind pattern followed a helical orientation with an approximate 36-degree fiber angle relative to the chamber axis as shown in Figure 2 on a 2k chamber and 40-degree fiber angle on the 7k (Figures 14-15). These helical tows covered the chamber as a first ply. The chamber is then hoop wound (Figures 3 and 17) and the helical-hoop pattern was repeated to yield a total of four plies.

Following winding and resin application, the overwrap was either rotisserie oven cured at NASA Marshall Space Flight Center (MSFC) or wound with shrink wrap and rotisserie oven cured at Kord Technologies. All cure cycles followed the resin manufacturer’s recommended cure cycle. The shrink-wrap aided consolidation and provided a smooth surface finish to the cured part. In the case of the 5250-4 BMI, the shrink-wrap was removed prior to elevated temperature post cure.

3.1 Composite Overwrap Manufacturing: 2k Decoupled

Steps from the winding process described above are shown in Figures 2-4 for the 2k Chamber.

Figures 2-4. 2k Filament Winding Process

The quantity of resin required to attain 40 wt. % resin content was calculated prior to winding. This amount of resin was weighed into a jar and heated on a temperature-controlled hotplate for 828/W resin system. The resin was applied to the fiber using a resin bath located on top of the filament winding head.

In order to achieve the lowest angle as possible on the cylindrical areas of the chamber, a dome was used to wind over the forward end of the chamber for the helical layers. This approach was taken as ridges on the forward end of the chamber allow the hoop layer to lock in the helical tows before that layer is cut to fit the length of the cylinder. After the hoop layer locks in the helical layer it can be trimmed down with a razor blade as seen in Figures 3 and 4 before oven cure. These ridges were an effective manufacturing aid for the 2k chamber and were therefore printed into the larger 7k and 40k chambers. The wound and cured overwrap on a 2k chamber is shown in Figure 5.

Figure 5. Final 2k Chamber Post Cure

3.2 Composite Overwrap manufacturing: 7k Chamber

Plastic 3D printed models have been a significant part of the composite overwrap process development. These low-cost versions of the surface profile provided a realistic practice mandrel to wind over before the copper chambers were available. One of the main challenges facing the composite overwrap is the manifolds and inlets and outlets to the manifold. Having a representative model allows the engineer to develop and optimize the process conditions before overwrapping the copper chamber test article.

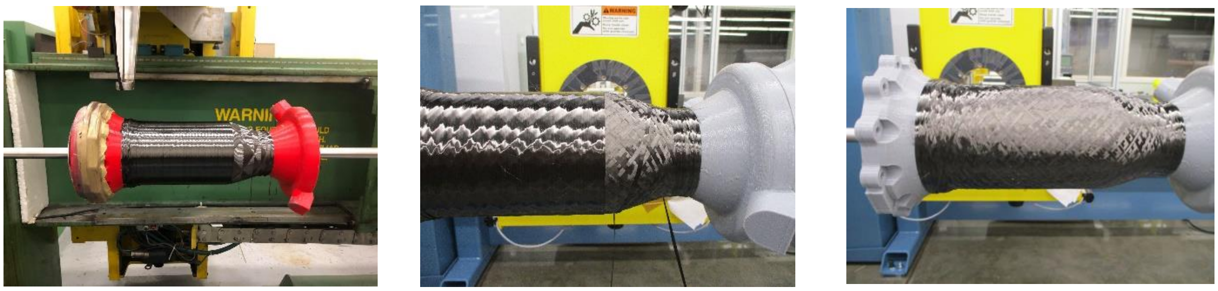


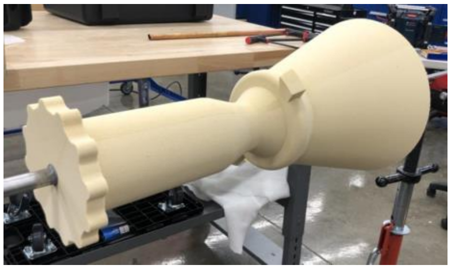
Figure 6-8. Plastic 3D Printed Model for Fiber Path Development with Helical Layer

Figure 6 is a 3D printed plastic model manufacturing demonstration done at MSFC. Kord Technologies also made use of the plastic models as seen in Figures 7 and 8. The filament winding process development at Kord Technologies started with a 3D printed plastic chamber to represent the complexities in the geometry expected of the copper chamber. The rapid availability of this material allowed for quick fiber path and machine movement development while an additional high temperature practice model was procured for wet winding and curing trials.

Using the outer profile of the chamber, a low angle (40°) helical fiber path and circumferential (90°) path were generated for complete coverage. In the helical layer, the 90° turnaround location was not sufficient for the design, the winder carriage movement was expanded to allow for a true 40° along the entirety of the composite target location.

3.2.1 Wet Wind Process Development Foam Mandrel

Once the fiber layup was successfully defined using the plastic 3D model, a high temperature foam (FR-4718) closed cell polyurethane model that had been machined with a representative geometry was used for wet-winding and cure trials (Figure 9). The foam mandrel was wrapped with Teflon tape to simulate the unbonded surface of the copper surface (Figure 10). Due to the difference in surface friction of the Teflon tape and the 3D printed plastic, the addition of pin tape was required at the forward end of the part to hold the fiber at the low angle before turnaround and maintain a low angle along the full composite coverage area. Pin tape was bonded to the forward end using a high strength adhesive. A brass shim was secured aft of the pin tape at the composite start location, and the location was recorded and marked using a laser on the carriage. The brass shim was used to protect the underlying structure when the composite was cut with a razor blade to remove the pin tape.



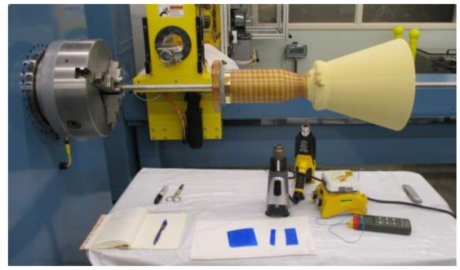


Figure 9. High Temperature Foam Mandrel   Figure 10. Foam Mandrel with Teflon Tape

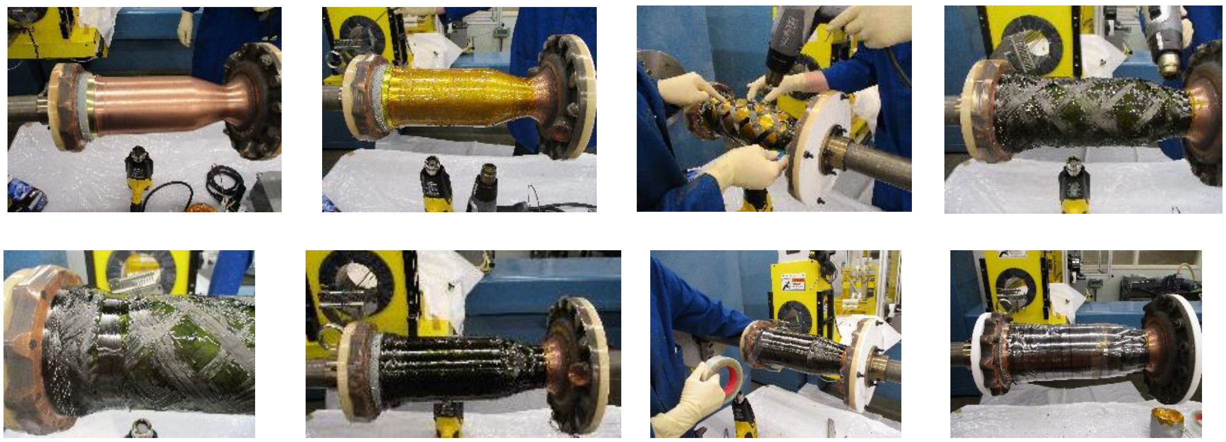
The 5250-4 BMI resin was weighed out and heated in a 200 mL beaker using a controllable heating mantel to 93 ℃ (200 °F) where the viscosity was optimal for manual application. As a predictable but not controllable method for resin content, the resin mass in the beaker was measured before and after the wind and used with the known volume of fiber on the part to calculate an approximate resin content value. A thin layer of heated resin was applied to the surface of the Teflon taped foam to provide a tacky surface that would reduce slippage and allow for resin to flow up through the layers and impregnate the fiber. Heat was applied to the surface of the wet composite using a heat gun to keep the viscosity of the resin low enough to flow through the layers uniformly. As more fiber was added and the layers became dry, more resin was added to the surface and spread around the circumference using a plastic squeegee. Again, heat guns kept the resin flowing and encouraged uniform saturation of the layers. The composite layers consisted of a helical layer that was held in place at the forward end with pin tape and followed by a hoop layer that was used for circumferential support as well as to act as a mechanical lock at the forward end to prevent bridging at the hump at the forward end. A layup of [±40º, 90º, ± 40º, 90º] was sufficient to reach the required composite thickness of the design.

The wet composite was trimmed at the brass shim location using a razor blade as the chamber rotated on the winder and the pin tape was removed prior to cure. To consolidate the material and provide a uniform surface, 20% polyester shrink tape (1.25 in. width) was applied to the chamber cylinder surface via the barber pole method, overlapping the width by half with each wrap. Due to the changing diameter associated with the geometry of this design, the shrink tape was applied to the part in two sections: the cylinder and the throat. To prevent the shrink tape from sliding down the slope of the throat, a wider shrink tape (2.5 in. width) was used at the throat and preshrunk to hold the shape before cure. Trials are in progress to optimize the use of shrink tape with more complex geometries and steeper slopes. The foam wet-winding part was cured to the manufacturer’s recommendation thermal schedule.

Figure 11. Foam Mandrel with Final Cure Part

3.2.2 Wet Wind Deliverable-Copper Chamber Test Article.

Once all the dry and wet winding parameters were established and a model successfully cured, all processing steps learned from the prior chamber models were applied to the copper test chamber. The composite overwrap was required to be unbonded, so the copper surface required preparation as described in section 2.2 to allow for release from the resin with the brass shim bonded as well. The pin tape bond location at the forward end was not coated with mold release.



Figures 12-19. 7k Test Article Manufacturing Steps

The resin was applied to the prepped copper surface (Figure 13) and the wind was repeated per the same processing steps as the foam chamber, pin tape and brass shims were removed and shrink tape was applied. Figures 14-15 show helical winds on the chamber while 16-17 show hoop. The part was cured under rotation at the vendor recommended thermal schedule provided in Table 2 (Cure). After the initial cure, the tooling was removed, and the part was post cured free standing with the schedule in Table 2 (Post Cure).

Table 2. 7k Cure Schedule

Cure	
Temperature ℃ (°F)	**Duration (min)**
Ramp 5/min to 121 (250)	36
121 (250) dwell	45
Ramp 5/min to 190 (375)	25
190 (375) dwell	360
Ramp down -5/min to 21 (70)	75
Total Cure Time	541
Post Cure	
Ramp 5/min to 227 (440)	73
227 (440) dwell	360
Ramp down -5/min to 21 (70)	73
Total Duration	506

Figure 20 shows the completed part at Kord before testing at MSFC.

Figure 20. Final Composite Overwrap Chamber Post Cure

3.3 Composite Overwrap Process Development: 40k Chamber

The 40k chamber has presented the team with an extra challenge of a port hole on the surface of where the overwrap is supposed to lay. NASA and Kord have been investigating a multitude of different winding styles to accommodate for the disruption in the winding pattern. Further documentation of the 40k processing with be included in future papers.

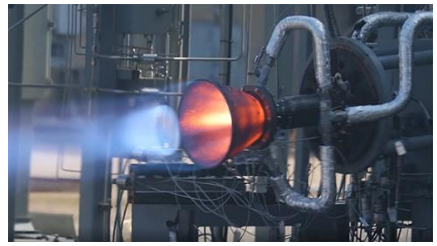
4 TESTING RESULTS

4.1 Hot Fire Testing

Kord Technologies completed the composite overwrap structural jacket on a 7k lb_f additive manufactured GRCop-42 chamber in January of 2021. This chamber was used in two separate hot fire tests.

4.1.1 Hot Fire Test of 7k Chamber February 2021

This manufacturing technology demonstration for the composite overwrap structural jacket was used in a single test made available as another test program was completed and had one hot fire test slot remaining on February 25, 2021 (Figures 21 and 22). Before testing, the composite was completely unbonded and was shown to move freely around the chamber. This test ran for approximately 10 seconds before it was terminated by observers when the coolant outlet temperature exceeded the predetermined acceptable upper limit form this first test.



Figures 21-22. February 7k Hot fire Test

The composite overwrap functioned very well and contained the chamber pressure even though during this test the composite was exposed to ~249 ℃ (~480 ℉). Which is a temperature greater than the maximum short-term material operating temperature of 232 ℃ (450 ℉). After the test, it was observed that the composite overwrap was no longer able to move freely around the chamber.

4.1.2 Hot Fire Test of 7k April 2021

A second test series with the same chamber were fully accomplished on April 2, 2021 with a total of 3 starts and 125 seconds of cumulative mainstage duration as seen in Figure 23. Chamber pressures of up to 755 psi at a mixture ratio of 3.57 for over 60 seconds were achieved. Chamber surface roughness reductions on this hardware brought the maximum coolant outlet temperature (a proxy for composite bond interface temperature) to a maximum of 193 ℃ (380 ℉). This temperature is within the composite specifications and is representative of temperatures required for hardware of this design.

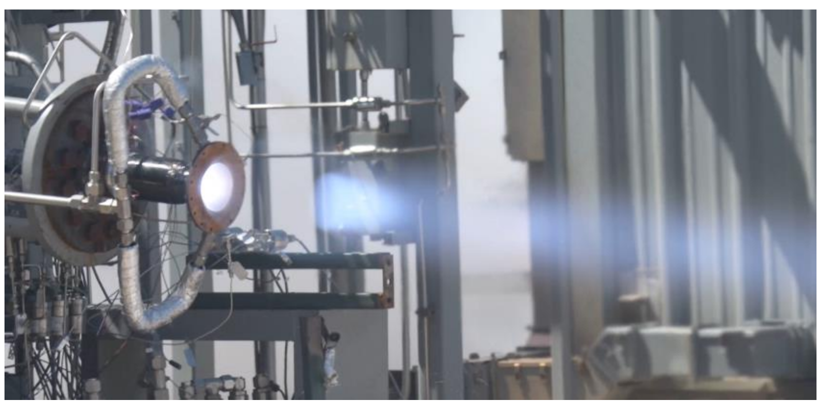


Figure 23. April 7k Hot fire Test

Visually the composite had no damage post-test. Before and after each hot fire test a series of NDE thermography photos were taken of the chamber. This was done in order to help the team further understand how the composite was being affected by these cryogenic and hot fires cycles.

4.2 NDE Results

Flash thermography Non-Destructive Evaluation (NDE) was performed at MSFC at various points during testing. For this method of NDE the part at ambient temperatures is exposed to a quick flash excitation source to apply heat to the part. Then a thermal camera records the temperature of the part at various times as it cools.

4.2.1 7k Flash Thermography NDE: Cooling Rate

Before and after the hot-fire tests of the 7k chamber, flash thermography NDE was performed on the composite wind. Figure 24 shows results of flash thermography (cooling rate) from before the hot fire test, after the first hot-fire test, and following second hot-fire tests. The first row is the before and the second row is the after the first test in Feb of 2021, while the third row is after the second test in April 2021. The forward and aft areas of the chamber are also labeled. For full visualization of the chamber, four flash thermography tests were performed where the chamber was rotated 90° after each test. The color map is from -0.4 (black) to -0.9 (bright red), such that a flatter slope (aka cooling rate) (closer to -0.4) is assigned a darker color and a steeper negative slope (closer to -0.9) is assigned brighter red color. With a flatter slope, the darker areas indicate less intimate contact between the overwrap and chamber as a gap between overwrap and chamber slows cooling. With a steeper negative slope, the brighter areas indicate more intimate contact between the overwrap and chamber because of the rapid cooling caused by the underlying copper chamber.

The goal with this overwrap is to be unbonded from the chamber, which was observed prior to the 10 second hot-fire test in February 2021 despite having some intimate contact around the throat. The second row shows significantly more intimate contact with the chamber after hot fire around the throat, though having this close contact does not necessarily mean the overwrap is now bonded to the chamber. A continuing trend of the chamber and the overwrap being in more intimate contact with each other is observed after the second hot fire as shown in the 3rd row. The dark areas near the aft end after both rounds of hot-fire tests are artifacts in the images resulting the overwrap being thinner in these areas and do not indicate that the overwrap and chamber are disbonded in these areas.

The changes in the results from before to after hot-fire tests, in reference to amount of contact between the chamber and overwrap, is believed to be a change in the copper chamber and not the overwrap itself. The flash thermography results indicate that the throat region and lower area of the cylinder region are slightly enlarged after each hot fire test, which would cause more intimate contact between the overwrap and chamber.

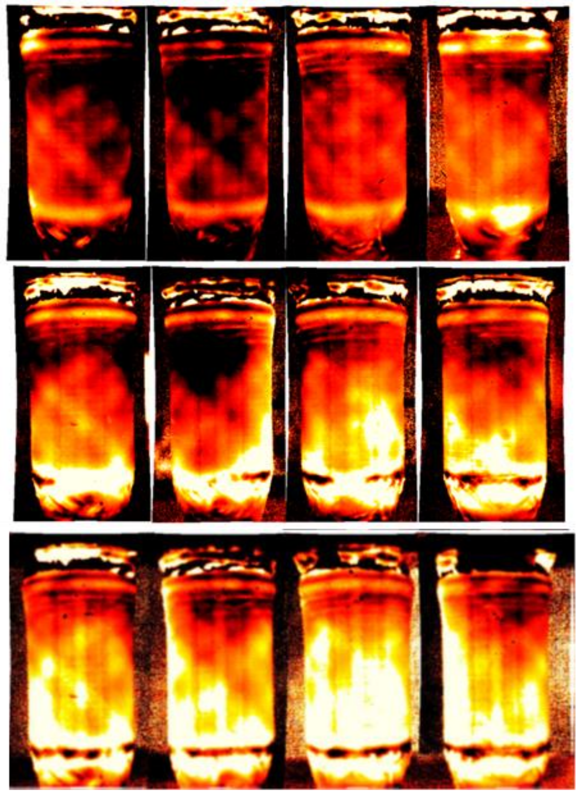
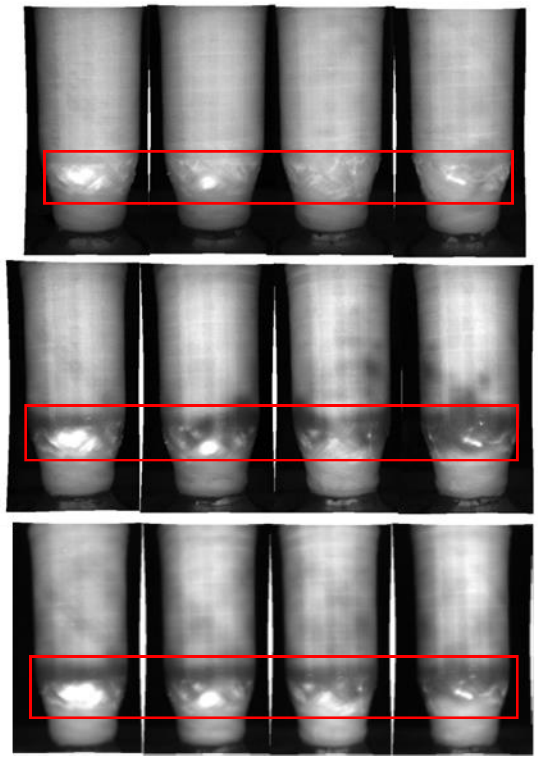
Pre-Hot Fire Test		Forward
		Aft
Post Hot Fire Test 1		Forward
		Aft
Post Hot Fire Tests (Round 2)		Forward
		Aft

Figure 24. 7k Flash Thermography NDE (Cooling Rate) Progression through Hot Fire Tests in February and April of 2021

4.2.2 7k Flash Thermography NDE: Cooling Amplitude

Figure 25 shows results from the flash thermography (cooling amplitude aka temperature) test from before the hot fire to after the first and second hot fire tests. The first row is before the test, while the second row is after the first test, and the third row is after the second round of hot fire tests. The main piece of information learned on this NDE test is the high porosity and/or delamination areas (seen as white areas in the images) near the aft end of the chamber. These areas are indicated in the red boxes. The high temperatures (white color) at these areas during the cooling process indicate that heat is being trapped in the overwrap, which is an indication of a defect (e.g., porosity, delamination) in the composite overwrap.

This is most likely caused by a slip in the shrink tape used when curing the overwrap. The area of high porosity and/or delamination appears to grow after each of the hot fire tests. This highlights the importance of the shrink tape application process. Steps are being taken to improve this for the 40k and other 7k chambers as mentioned in section 3.2.1.

<table>
<tr><td rowspan="2">Pre-Hot Fire Test</td><td rowspan="6"></td><td>Forward</td></tr>
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<tr><td rowspan="2">Post Hot Fire Test 1</td><td>Forward</td></tr>
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<tr><td rowspan="2">Post Hot Fire Tests (Round 2)</td><td>Forward</td></tr>
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Figure 25. 7k Flash Thermography NDE (Amplitude) Progression through Hot Fire Tests in February and April of 2021

5 CONCLUSION

There has been substantial progress made in the development of the composite overwrap on a 3D printed copper combustion chamber due to the high interest of using its high strength to weight ratio compared to previous metal jackets. Manufacturing process development, materials performance requirements, and additively manufacturing surface preparation are the key drivers for this composite overwrap advancement. Being able to directly 3D print ridges in the chamber for overwrap stability and support is one of the biggest takeaways from the 2k development process. The 7k utilized added steps such as pin tape, resin application, and shrink wrap. Hot fire testing has been successfully completed in both 2k and 7k scales. All the process developments discussed will be utilized in the manufacturing development of the 40k chamber which will experience an even more challenging loading environment than hardware tested to date. MSFC was also able to gather NDE flash thermography images before and after each hot fire test to supplement what RAMPT learned through the manufacturing progression. With the successful builds and hot-fire testing of both the 2k and 7k chambers, the building blocks of the RAMPT approach (3D printed combustion chamber and nozzle and composite overwrap) have been proven and the lessons learned will be applied to the larger thrust chambers (40k-lb_f thrust) moving forward.

6 References

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